A Wideband Tape and Transport Diagnostic Method

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Abstract

An analog magnetic tape recorder introduces more types of distortion into music recordings than any other component in the signal chain. An impressive array of instrumentation devices and standards have been developed for measuring electronic circuitry (THD, IM, SID, noise weighting filters, etc.), but meaningful evaluations of the magnetic head-to-tape interface have not received much attention. A new form of test instrument, a Tape and Transport Diagnostic System (T^2DS), which measures both amplitude irregularities due to tape oxide non-uniformities and frequency deviations due to transport speed perturbations, is herein described.

Introduction

A magnetic tape recorder introduces distortions to recorded material that are unique in the recording chain. Even if the recorder design engineer were able to completely remove all distortions from the record and reproduce amplifiers of the recorder, a broad range of distortions would still remain. Only one small portion of these distortions has been studied to any extent — conventional low-band flutter — but even this standardized measurement has been corrupted by the introduction of 'weighted flutter', a virtually useless specification when dealing with the critical evaluation of professional equipment. A more comprehensive method of measuring all of the sidebands or spurious frequency components created by amplitude and frequency modulations introduced at the magnetic tape-to-head interface is discussed herein, and the effects will be demonstrated in the presentation.

Sideband Related Distortions

Contrary to your local audio equipment salesman's opinion, magnetic tapes and tape recorders are not perfect. Magnetic tapes suffer from dropouts, magnetic dispersion anomalies, poor slitting, and surface roughness; recorders contain eccentric rotating components, defective bearings, torque and speed variations in drive motors, and even scraping of 'rough' tape surfaces against stationary components. As shown in the Appendix, all of the above imperfections create extraneous or sideband frequencies added to the normal musical content of a recording. Unlike some other forms of distortion, these new frequencies are not at all musically or harmonically related to the desired musical program. In fact, these sidebands are extremely obvious and objectionable, yet also difficult for even a trained listener to identify. Perhaps the reason for this apparent contradiction between perception and identification is that natural phenomena are usually linear operations that do not produce these sideband structures. Thus, when such components do occur, whether in a recorder or in a special effect for a science-fiction movie, the listener responds quickly to the 'unnatural' sound but is unable to identify the cause or source.

Wideband Flutter

A good starting point for this discussion is the well-known but little-understood 'flutter meter'. This device measures speed variations that produce frequency shifts (perceived as pitch changes) of the musical tones in a recording. Since the amplitude of these shifts is on the order of 0.1 %, the change is only about $1/60^{\text{th}}$ of a halftone. The listener does not perceive this error as a pitch shift, but does respond to the extra components created at the music frequency plus and minus the frequency of the flutter component. As an example, a pure A440 note in the presence of a 120 Hz flutter would actually consist of a strong component at 440 Hz and two weak components at 320 Hz and 560 Hz. (Additional components of diminishing amplitude are also present at 120 Hz intervals from 440 Hz.) These new components 'broaden' the perceived tone, or make it sound 'fuzzy'.

If the flutter rate is very low — less than a few hertz — the listener can actually follow the pitch change. This effect is called 'wow' (pronounced as in an Indian pow-wow). At slightly higher flutter rates of 5 Hz to 50 Hz, the effect is so fast that the listener observes a 'fluttering' of the tone. Above approximately 50 Hz the listener responds to the sidebands as 'fuzziness'.

The upper frequency limits for flutter created by mechanical components are primarily a function of rotational rates of the balls inside ball bearings and the torque pulsation rates at even harmonics of the power-line frequencies. A typical limit that is embodied in the NAB and IEC flutter standards is a lowpass function cutting off at approximately 250 Hz.

Unfortunately, tape recorders are not taught that they cannot possess flutter components above 250 Hz. On the contrary, the flutter spectrum extends throughout the normal audio spectrum! The source of the high-frequency or 'scrape flutter' components is not mechanical rotation, but rather scraping of the tape surface against stationary heads and guides. The tape — an elastic filament under tension — vibrates at frequencies determined by the density, modulus of elasticity, tension, and 'length of free span' of the tape. A following detailed consideration of each of these factors may aid the reader in diagnosing scrape flutter problems.

The *density* of the tape is really the mass per unit length, determined by:

1. the 'recipe' used to mix the magnetic oxide/binder system that is coated onto the polyester backing,
2. the thickness of the coating,
3. the density of the polyester backing, and
4. the thickness of the polyester base.

Lower densities produce higher-frequency scrape flutter components.

The *modulus of elasticity* of the tape is primarily determined by the base-film material, but is modified by the elasticity of the magnetic coating. Long-play tapes have thinner backings, which vibrate at lower frequencies. Tensilizing or pre-stretching polyester base films nearly triples the modulus of elasticity. (The modulus of elasticity in the direction of tape travel is usually different from the modulus across the width of the tape, owing to the anisotropic nature of extruded polyesters.)

The *tension* in the tape may vary from the beginning to the end of a reel. This can produce a change in the flutter spectrum throughout the length of a reel. Low tensions reduce the flutter frequencies and minimize the exciting frictional forces.

The *length of free span* is the distance between massive rotating elements (rollers) that are analogous to fixed supports on a vibrating string. These rotating elements must have enough inertia to absorb the vibrational energy of the tape as the vibration tries to move across the roller. The contact pressure on the roller must also be high enough to hold the tape firmly to the roller surface. As an example of this last condition, note that the large-inertia roller on the left side of many older tape transports will actually generate scrape flutter while the roller is accelerating to operating speed — a condition lasting as long as 15 seconds after the play mode is initiated. 'Scrape flutter idlers' are rollers inserted between the heads of a recorder to break the long free span of tape from the supply reel to the capstan into shorter 'subspans'.

Another consideration is the magnitude of the exciting force. The frictional drag on the tape from sliding over stationary surfaces is a primary factor in determining the amount of scrape flutter excitation. A quick 'figure of merit' for comparison purposes can be calculated by measuring the angle of tape wrap around all of the stationary guides and heads between the supply reel and the capstan. The sum of all of these angles is proportional to the frictional drag. A good machine may have as little as 25° of wrap, but 'bad' machines may have 270°. The roughness of the tape surface and guides, and the affinity of the tape and guide materials, also determine the frictional force present to excite scrape flutter. Very rough surfaces are raspy; ultra-polished tape surfaces may suffer from a stick/slip phenomenon that generates jerking as the tape repeatedly tries to stick to a surface and is then broken away to slide freely.

Occasionally recorders will 'invent' new ways to confound the designer. One such example is the squealing of rubber pinch rollers on various brands and types of tape. This squeal produces excessive scrape flutter that is permanently recorded on the tape as frequency modulation at the squeal frequency.

Guidelines for selecting low scrape flutter recorders are straightforward — pick a deck with

1. few stationary surfaces and guides,
2. small angles of wrap around the stationary guides,
3. short spans of tape between rollers,
4. low tape tension, and
5. servo-controlled D.C. motors.

Extra heads for alternate formats or bidirectional operation are detrimental if they are not isolated by a capstan. 'Closed-loop' machines that have relatively short spans of tape locked to capstan surfaces at both ends of the head assembly provide very good performance if the tension is properly controlled.

Tape Related Sidebands

In addition to flutter-related sidebands, the magnetic recording process suffers from a host of sidebands resulting from amplitude variations due to tape imperfections. The sidebands created by these tape-related amplitude-modulation (AM) terms and the narrowband FM flutter terms are similar in spectrum, with the exception of the phase of the lower sideband. Since the ear is a 'spectrum analyzer' working in the frequency domain, we perceive AM and FM sidebands similarly. The maintenance technician and designer, however, are keenly interested in the type and source of the sidebands. For example, reducing scrape flutter will not alleviate an AM sideband problem created by poor oxide dispersion on a tape specimen. Herein arises the need for a diagnostic tool that distinguishes between

AM and FM sidebands. (The amplitude display of a spectrum analyzer cannot make this distinction, since it contains no phase information.)

Before examining an instrument that fills this need, let us investigate the causes of AM sidebands. Tape is a mixture of oxide and glue smeared onto a sheet of plastic. A 'perfect' magnetic recording requires that the magnetic performance of a tape be identical at every point on the tape surface. This would imply no variation in any of the following:

1. ratio of oxide to binder,
2. magnetic property of each oxide particle,
3. thickness of the oxide layer,
4. orientation of the oxide particles,
5. surface smoothness, and
6. density of the oxide after calendering.

Additional problems related to the mechanical contact of the tape with the head are:

7. poor slitting, including ruffled edges, 'country laning' or low-frequency slitting undulations, and cupping of the tape across its width,
8. worn heads with flat faces or 'horns' on the edges of non-undercut heads,
9. inadequate wrap of the tape on the heads,
10. racking error (gap not at the apex of wrap),
11. zenith or azimuth errors making the tape ride up and slip down on the heads in jerks, and
12. low tension.

All of these tape and transport problems produce a modulation envelope that creates amplitude errors in the music. The ear can easily detect the resulting AM sidebands.

The T^2DS Approach

A diagnostic device to measure all of the sideband effects described above would need to be capable of measuring any sideband created within the audio band. A practical limit arises, however, when trying to design a device that will measure the AM and FM content of a test tone. The recorder system must be capable of passing the upper sideband at the maximum modulation frequency of interest. Assuming a 'safe' upper limit of 18 kHz for a professional recorder, and recognizing that Shannon's sampling theorem requires a 'carrier' at twice the modulation frequency, a reasonable choice is a 12.5 kHz test tone and a demodulated bandwidth of 5 kHz.

If no passband filter from 7.5 kHz to 17.5 kHz is used on the recovered tone from the recorder, 'alias' frequencies will be introduced into the measurement. Since these alias components are actually images of modulation products, they are retained in the T^2DS processor and included in the quantitative measurement. (In reality, the scrape flutter content decreases as frequency increases due to mechanical dissipation in the tape. The contribution of flutter terms near 12.5 kHz is minimal.)

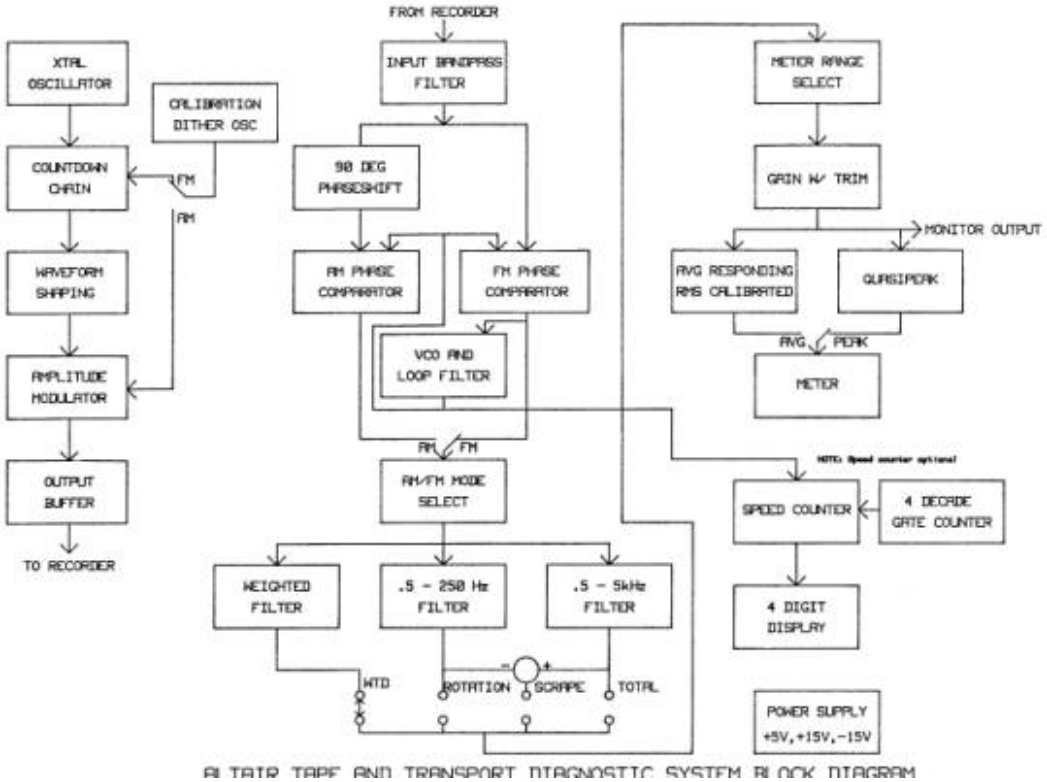

Figure 1. Altair Tape and Transport Diagnostic System block diagram.

The T^{2}DS block diagram in Figure 1 contains the following elements:

1. a 12.5 kHz crystal-controlled reference oscillator producing low residual AM and FM noise, with built-in AM and FM calibration modes,
2. an AM demodulator,
3. an FM demodulator,
4. selectable low-pass, high-pass, and weighting filters, and
5. metering circuitry for average and peak measurements.

The system provides independent AM and FM measurements in the passbands of 0.5 Hz–250 Hz (mechanical components only), 250 Hz–5 kHz (scrape components only), and 0.5 Hz–5 kHz (all components combined). A weighting filter is included for conventional NAB and IEC weighted flutter measurements. Residual measurement noise for the widest bandwidth is typically 0.005 % RMS for FM and 0.1 % for AM, which is approximately 20 dB below the best transport and tape tested to date.

Summary

The Altair Tape and Transport Diagnostic System permits far more critical analysis of magnetic recording systems than was hitherto available in a single inexpensive instrument. In addition to many professional master-recorder applications, the T^{2}DS permits checking high-speed machines such as duplicator master and slave transports running at 32 times normal speed, and analog instrumentation recorders.

As a magnetic-tape evaluation and quality-control device, the T^{2}DS provides a convenient tape-testing method that is exactly reproducible by both vendor and purchaser, permitting reproducible tape performance data to be sent from the user to the manufacturer for the first time.

Test results to date indicate a far more positive correlation between T^{2}DS measurements and the subjective evaluations of trained listeners than is possible with conventional NAB/IEC flutter meters. Combining a 20-fold increase in flutter measurement bandwidth with the tools to evaluate wideband AM performance is indeed worthwhile.

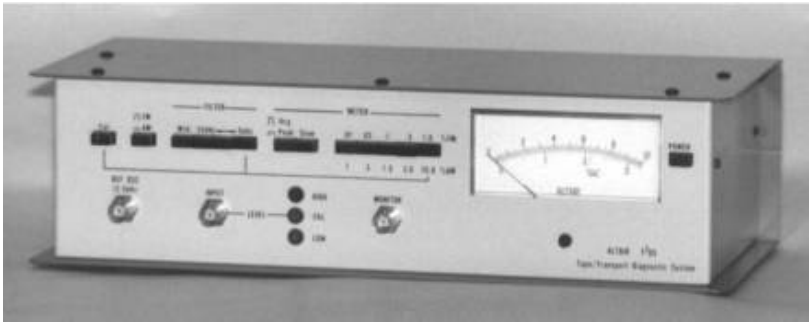

Figure 2. The Altair T^{2}DS Tape/Transport Diagnostic System.

Appendix — Derivation of the AM and FM Sidebands

AM

Assume that we are recording a pure reference tone $s(t)$ of $f_{\mathrm{REF}} = 12.5\,\mathrm{kHz}$ and amplitude A_{REF} on a tape recorder:

$$s(t) = A_{REF}\cos 2\pi f_{REF}\,t$$

If amplitude irregularities such as tape slitting produce a periodic level change of peak amplitude A_{AM} at a rate f_{AM}, the expression for the modulated tone is:

$$s(t) = A_{REF}\{1 + A_{AM}\cos 2\pi f_{AM}\,t\}\cos(2\pi f_{REF}\,t)$$

Expanding this expression and using trigonometric identities yields:

$$s(t) = A_{REF}\{\cos 2\pi f_{REF}\,t + A_{AM}\cos 2\pi f_{AM}\,t\cos 2\pi f_{REF}\,t\}$$

$$= A_{REF}\cos 2\pi f_{REF}\,t + \frac{A_{AM}}{2}\cos 2\pi(f_{REF} + f_{AM})\,t + \frac{A_{AM}}{2}\cos 2\pi(f_{REF} - f_{AM})\,t \qquad (1)$$

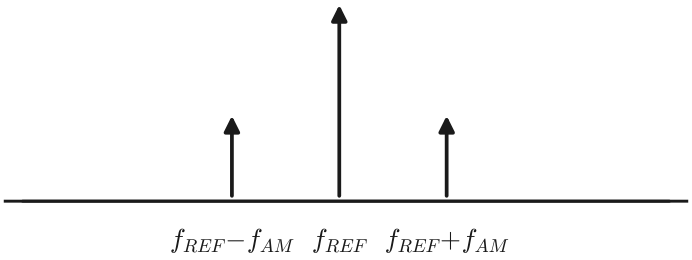

Figure A1. AM spectrum of Eq. (1).

To demodulate an AM signal, multiply Eq. (1) by $\cos\ 2\pi f_{\mathrm{REF}}t$:

$$s(t) = A_{REF}\cos^2 2\pi f_{REF}\,t + \frac{A_{AM}}{4}\cos 2\pi(f_{REF} \pm f_{AM})\,t + \frac{A_{AM}}{4}\cos 2\pi(0\cdot f_{REF} \pm f_{AM})\,t$$

The first term can be replaced by $\frac{A_{REF}}{2}(1 + \cos 2\pi\cdot 2f_{REF}\,t)$. Low-pass filtering below f_{REF} leaves only the terms at $\pm f_{\mathrm{AM}}$.

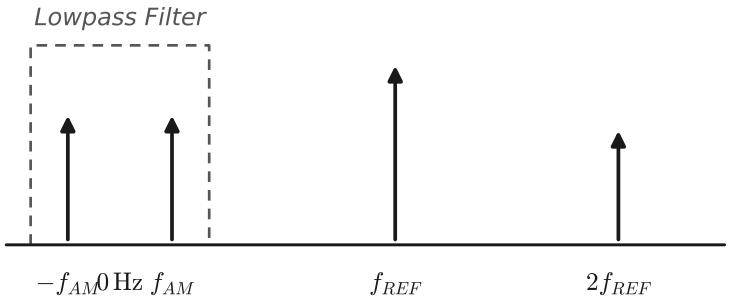

Figure A2. Demodulator output spectrum.

High-pass filtering the demodulator output with a coupling capacitor leaves only the desired AM components.

FM

For frequency modulation, the instantaneous frequency of the signal is deviated from the nominal reference frequency by an amount proportional to the amplitude of the flutter component, at a rate equal to the flutter frequency, i.e.,

$$f(t) = f_{REF} + A_{FM}\, f_{REF} \cos 2\pi f_{FM}\, t$$

where A_{FM} is the peak value of FM (% flutter).

The instantaneous phase angle of the FM signal can be found by integrating the above:

$$\theta(t) = 2\pi \int_0^t f(t)\, dt$$

$$= 2\pi \int_0^t f_{REF}\, dt \;+\; 2\pi \int_0^t A_{FM}\, f_{REF} \cos 2\pi f_{FM}\, t\; dt$$

$$= 2\pi f_{REF}\, t \,|_0^t \;+\; 2\pi \left\{ \frac{A_{FM}\, f_{REF}}{2\pi f_{FM}} \sin 2\pi f_{FM}\, t \right\}_0^t$$

$$= 2\pi f_{REF}\, t \;+\; A_{FM} \frac{f_{REF}}{f_{FM}} \sin 2\pi f_{FM}\, t$$

Define $\beta = \frac{A_{FM}\, f_{REF}}{f_{FM}} = \frac{\Delta f}{f_{FM}}$ as the 'modulation index'. The flutter-containing signal can now be expressed as:

$$s(t) = A_{REF} \cos\left(2\pi f_{REF}\, t + A_{FM} \frac{f_{REF}}{f_{FM}} \sin 2\pi f_{FM}\, t \right)$$

Expanding this using the identity for cos(α + β) yields:

$$s(t) = A_{REF} \left\{ \cos 2\pi f_{REF}\, t \cos\left(A_{FM} \frac{f_{REF}}{f_{FM}} \sin 2\pi f_{FM}\, t \right) - \sin 2\pi f_{REF}\, t \sin\left(A_{FM} \frac{f_{REF}}{f_{FM}} \sin 2\pi f_{FM}\, t \right) \right\}$$

Since peak flutter in a tape machine is typically less than 0.1 %, and for scrape flutter the range of f_{FM} is 250 Hz $< f_{\mathrm{FM}} <$ 5 kHz, the term $A_{\mathrm{FM}} f_{\mathrm{REF}}/f_{\mathrm{FM}}$ is less than

$$A_{FM}\frac{f_{REF}}{f_{FM}} < .001\left(\frac{12.5\text{ kHz}}{250\text{ Hz}}\right) = .05$$

(very narrow-band FM).

This upper bound simplifies the first product in $s(t)$, since

$$\cos\left(A_{FM}\frac{f_{REF}}{f_{FM}}\sin 2\pi f_{FM}\,t\right) > \cos .05 \approx 1$$

and allows us to use the small-angle approximation sin $\theta \approx \theta$ in the second product to yield

$$\sin\left(A_{FM}\frac{f_{REF}}{f_{FM}}\sin 2\pi f_{FM}\,t\right) \approx A_{FM}\frac{f_{REF}}{f_{FM}}\sin 2\pi f_{FM}\,t$$

The resultant approximation for $s(t)$ is:

$$s(t) = A_{REF}\left\{\cos 2\pi f_{REF}\,t - A_{FM}\frac{f_{REF}}{f_{FM}}\sin 2\pi f_{REF}\,t\sin 2\pi f_{FM}\,t\right\}$$

Expanding this expression with trigonometric identities yields:

$$s(t) = A_{REF}\left\{\cos 2\pi f_{REF}\,t + \frac{A_{FM}}{2}\frac{f_{REF}}{f_{FM}}\cos 2\pi(f_{REF}+f_{FM})\,t - \frac{A_{FM}}{2}\frac{f_{REF}}{f_{FM}}\cos 2\pi(f_{REF}-f_{FM})\,t\right\}$$

This narrow-band FM case is identical to the previously derived AM case, except that the lower sideband term at $f_{\mathrm{REF}} - f_{\mathrm{FM}}$ is reversed in polarity. The following phasor diagram shows the representation of the AM and FM components:

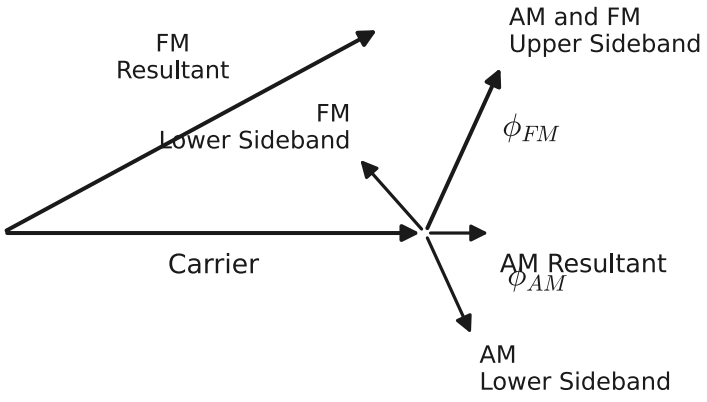

Figure A3. Phasor representation of the AM and FM sideband components.

Note that the FM sideband sum φ_{FM} is at right angles to the carrier and the AM sideband sum φ_{AM}. This quadrature relationship permits us to use similar detection schemes to separately detect the AM and FM components if we simply add a 90° phase shift to one of the signals prior to detection.

Altair T^2DS

Tape / Transport Diagnostic System

When professional tape recorders were first introduced thirty years ago, only rotating tape-drive components were checked for proper operation. In fact, fifteen years elapsed before the audio industry even recognized that scrape flutter was very important for 'clean' tape recordings. Unfortunately, an additional fifteen years passed before the introduction of an inexpensive flutter meter that will measure scrape flutter. But now, with the Altair T^2DS, we can easily measure flutter over a frequency range 20 times wider than the NAB/IEC standards permit.

But that is just the beginning. Now we can also test the amplitude performance of magnetic tape! Check for dropouts, bad slitting, poor tape-to-head contact, modulation noise, and even poor oxide mixing and coating. Even the smoothness and lubrication of the tape surface can be evaluated.

Theory of Operation

The analog magnetic-tape recording process introduces errors not found in electronic circuits — AMPLITUDE and FREQUENCY modulations. When a pure tone is recorded and reproduced, extraneous sideband frequency components are added to the original signal by transport and tape imperfections, producing a fuzziness or lack of clarity.

The T^2DS circuitry not only measures these sidebands, but also identifies whether speed changes or amplitude changes cause them. (Not even a $10,000 spectrum analyzer can do that!) By detecting 'in-phase' and 'quadrature' sideband components independently in the frequency band from 0.5 Hz to 5000 Hz (limited by the tape recorder's response cutoff at 18 kHz), the T^2DS presents a more complete picture of recorder and tape composite performance.

To permit comparisons with current published flutter specifications, the T^2DS also includes measurement modes equivalent to the standardized weighted and NAB/IEC measurements, but using the new reference frequency of 12.5 kHz.

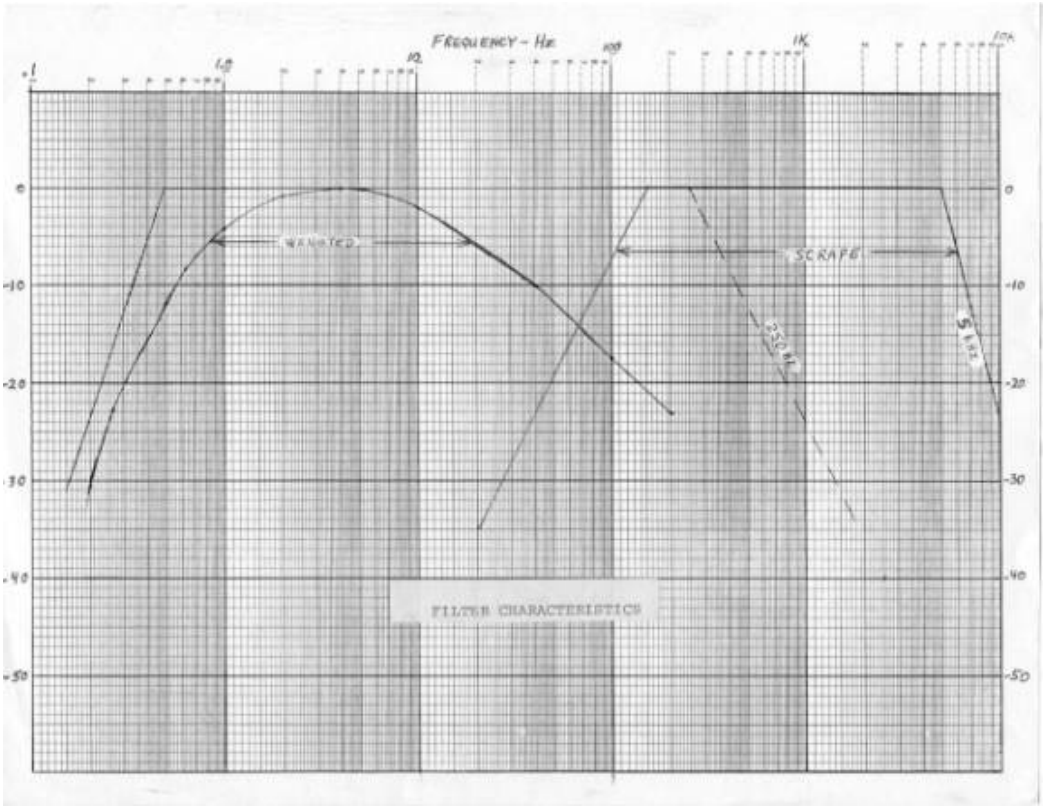

Figure 3. Predicted flutter measurement filter characteristics.

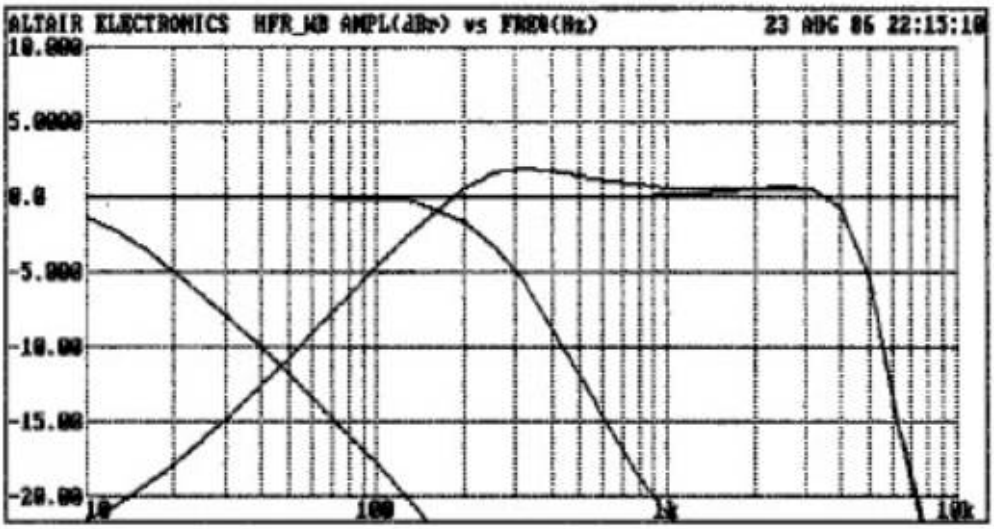

Figure 4. Audio Precision plot of the actual filter response.

Specifications

Oscillator

Crystal-controlled 12.5 kHz sinewave at −6 dBm (Note 1), with less than 0.001 % residual FM and AM noise contribution in measurements.

Calibrate modes provide a digitally derived 150 Hz square-wave frequency or amplitude modulation of the test signal for meter self-test.

Input Section

Input signal	12.5 kHz ±1 kHz at −6 dBm (Note 1)
Level indicators	LED signal-level indicators for correct input level (Cal), High level, or Low level below muting threshold
AM readings	require a nominal −6 dBm level ±1 dB for accurate readings
FM readings	accurate over an input range of −16 dBm to +14 dBm

Measurement Bandwidth (FM and AM)

Wideband	0.5 Hz to 5 kHz, for combined rotational and scrape components
Upper bandpass	250 Hz to 5 kHz, to isolate high-frequency components
Lower bandpass	0.5 Hz to 250 Hz, to isolate components due to rotating tape-drive members
Weighted	IEC/ANSI bandpass peaked at 4 Hz (included primarily for verifying specifications)

Meter Section

FM sensitivity	0.01, 0.03, 0.1, 0.3, and 1 % full scale
AM sensitivity	0.1, 0.3, 1, 3, and 10 % full scale
Demod output	provides the output signal after filters and meter-range selection for oscilloscope, spectrum analyzer, and/or loudspeaker. Full-scale meter deflection produces approximately 0.5 V RMS.
Characteristics	selectable for either full-wave-rectified average-responding, RMS-calibrated, or quasi-peak
Slow mode	provides extra damping to slow erratic meter fluctuations

General

Power	120 V, 50 or 60 Hz at 10 watts (240 V optional)
Size	13.5 W × 3.75 H × 6.0 D (inches)

Note 1. The test level of −6 dBm into 600 ohms (0.4 V RMS) is 10 dB below normal '0 VU' to avoid tape saturation of the test tone for 7.5 in/s recorders. Higher levels can be used at speeds above 7.5 in/s by raising the record level 10 dB and reducing the playback level sufficiently to light the 'Cal' level indicator.

Note 2. This instrument is intended for testing high-quality recording equipment to its operating limit. Slow-speed recorders such as cassette decks that cannot record and reproduce a 12.5 kHz tone with good signal stability may exceed the 10 % range of the AM section. Other versions of the T^2DS that use 6.25 kHz or 25 kHz signals are available.

Note 3. Accurate speed or drift measurements can only be made with an accurate reference tape and a digital counter.

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